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Physics Procedia 3 (2010) 161–167
Physics Procedia
www.elsevier.com/locate/procedia

International Congress on Ultrasonics, Universidad de Santiago de Chile, January 2009

Effects of nonlinearities in power ultrasonic transducers using time reversal focalization

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Abstract

This paper presents the characterization of nonlinearities in a Langevin-type ultrasonic power transducer using pulse excitations and a time reversal focalization technique. The nonlinear behavior of this power transducer is evaluated analyzing the signal obtained after focalization in time reversal process. In a linear regime, time reversal produces a focused pulse which amplitude and width depends only on the transducer's transfer function. When the supplied power is increased, three non-linear effects appear in the systems response. First, the focus shape loss symmetry respect to center; second, the focus amplitude increases without proportionality to input voltage, and finally, in the frequency spectrum appears harmonics of the thickness mode resonance frequency. The displacement at the end transducer surface was measured by an optical fiber vibrometer. Traditional frequency domain methods are also used to show phase variations close to each resonance frequency. The time reversal is implemented using the Frequency Domain Time Reversal (FDTR), that technique ensures the linear regime in the first step of the process.

Keywords: power ultrasound; non-linear behavior; time reversal

1. Introduction

Piezoelectric ceramics are usually modeled as linear when are excited by low electric fields, however non-linear effects appear for electric fields greater than 10 kV/m [1], these effects become more important in power ultrasound applications. To show these effects, a common transducer configuration used for ultrasonic welding applications is used. This kind of transducer is formed by a stack of piezoelectric rings sandwiched by two metallic masses, operates as a half wave length resonator, and is known as Langevin-type transducer. The metallic masses are used to give a pre-stress of about 30 MPa to the piezoceramics that support more compression than traction, and to allow better heat exchange. On the other hand, the effect of placing a piezoelectric ceramic stack between end masses is to decrease the operation frequency of the transducer. At one end of the transducer is attached a half wave length

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doi:10.1016/j.phpro.2010.01.023

mechanical amplifier to increase the displacement amplitude. For this type of transducer, nonlinear effects were originally studied in the frequency domain. Effects such as frequency shift in resonance modes and the "Jumping and Dropping" phenomena were reported by [2]. Modified constitutive equations of piezoelectric material can roughly predict nonlinear behavior [3].

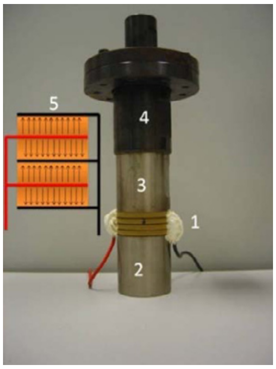

Fig.1 Langevin-type transducer. 1 Piezoelectric disk stack, 2 tail mass, head mass, 4 mechanical amplifier, 5 internal configuration of piezoelectric disk stack, arrows shows the polarization of the ceramics.

Recent works show the importance to characterize power ultrasonic transducer using sinusoidal burst instead of using continuous wave, because the use of burst minimizes the changes due to temperature increase [1] [5]. As the continuous wave, the tone burst characterization needs a frequency sweep near the resonance frequency, so this technique becomes time consuming [4]. Another possibility, not reported in the literature, is the use of a wideband pulse containing all the frequencies components near the resonance. The behavior of power ultrasonic transducer operating under high electric field excitation can modeled by nonlinear differential equations, but there are no closed analytical solution for this problem.

This paper proposes the use of a signal focused by time reversal to characterize the nonlinear behavior of the system [6]. Time reversal has the advantages of burst signals, in the sense that does not affect the temperature of the system and has the characteristics of wideband pulse in which all modes system are excited. But time reversal has two additional advantages because frequency modes are put in phase to add their effects in a given time. First, the amplitude obtained in the focus is several times greater than the one obtained using a short pulse and second, the amplitude width and shape of the focused pulse depend on the relative phase between the different components of the system transfer function. In this way, this technique characterizes the system both in amplitude and phase. To ensure the linear regime in the determination of the system's transfer function, we use the FDTR technique [7].

2. Non-linear effects in time reversal

At this point, the effect of errors in phase and amplitude in the time reversal signal received at the focus is analyzed [8]. Time reversal of acoustic waves starts with the measure of the impulse response *h(r,t)*. In the practice a delta-like pulse (short duration and high amplitude) is applied in the electrical terminals of the transducer. The received signal in the focal point r is recorded to be processed later. Subsequently this signal is time reversed and *h(r,T-t)* is retransmitted to the system. Here *T* is the temporal length of the signal. After the re-emission, the signal received at the focal point is recorded. This signal can be obtained theoretically using the convolution operator between time reversed signal and the impulse response

$$h(r,t)\otimes h(r,T-t)=\int_{-\infty}^{+\infty} h(r,\tau)\cdot h(r,t-T+\tau)d\tau \quad (1)$$

Making the change of variables *t-T=t'*, the product (1) is equivalent to the autocorrelation function of *h*.

The maximum is reached when t=0, this corresponds to a time equal to signals temporal length. We note that in the frequency domain, the time reversal process is equivalent to the product of the transfer function H(r,ω) by its complex conjugate H*(r,ω). This product cancels the phase of each component in the frequency response.

$$H(r,\omega)H^*(r,\omega)=|H|^2 \tag{2}$$

While the system remains linear, the spectrum of the signal recorded after time reversal process at the focus point is like (3). One manifestation of nonlinear behavior is the emergence of frequency modes which originally not exists in *H*, harmonics of the highest amplitude component are expected. In a linear system, the amplitude of the focused signal is proportional to the input voltage. If the focus amplitude depends on a non linear way on the input signal amplitude, the system behaves as non-linear. This behavior can be explained by the variations in the amplitude and phase of the frequency response components produced by the effect of the nonlinearities. To show this, a single component of the spectrum is analyzed. Is assumed that this component has an amplitude A_{linear} and phase φ_{linear} in the linear regime. The nonlinear effects introduces changes both in amplitude and phase, these are modeled by a Δ term. In this way, to obtain the focused signal using the convolution product, one of factors corresponds to the signal measured in the linear regime and the other term is affected by the presence of identification errors ΔA and $\Delta\varphi$. The result of performing the time reversal process in this case can be expressed as

$$y(r,t)=\left(A_0^2-A_0\cdot\Delta A\right)\cos\left(\omega_0 t+\Delta\varphi\right) \tag{3}$$

In a real time reversal process we have a sum of terms like (4) and focalization takes place at *t=0*. Then, the errors in amplitude affect the extent of the focus but not the symmetry around *t=0*. Otherwise, phase errors affect both amplitude and symmetry of the focused signal.

3. Frequency Domain Characterization

As a first step to characterize the system, we made a frequency sweep using a network analyzer HP4194A. The output of network analyzer is amplified by a broadband power amplifier, using a fix factor of 50 dB.

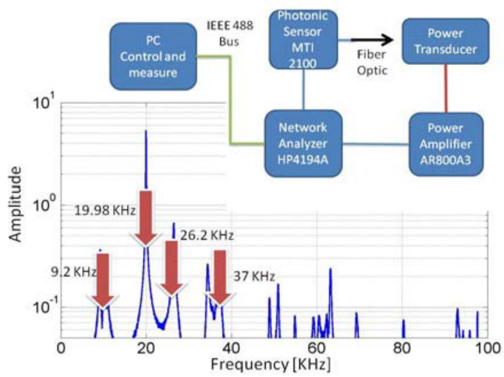

Fig.2 Transducer transfer function. Highlighted resonant modes are studied. In the upper part of the figure we show the experimental setup to measure the transfer function using HP4194A.

To determine the resonant modes a frequency sweep is made over the range [0-100 KHz]. See Fig. 2. Note that the system is highly tuned, with a maximum amplitude in 19.98 KHz. This maximum corresponds to the thickness resonance mode whit an amplitude several times higher as their neighbor resonances.

The four modes highlighted in Fig.2 are analyzed in detail. For all of them, the frequency is increased (sweep-up) and decreased (sweep-down) around the resonance frequency. The network analyzer output is starts in 50 mV and go to 1.2 V in steps of 100 mV.

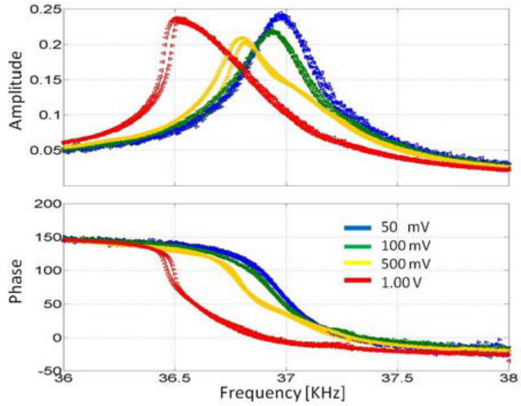

Fig.3 Nonlinear behaviour in 37KHz mode. See the different path form sweep-up “>” and sweep-down “<”.

In the four studied cases a similar behavior is founded with two main features. First, resonance frequency decreases as the system becomes more non-linear and second, sweep-up transfer function differs from that obtained performing a frequency sweep-down. To show that this effect is verified for all studied modes and not only in the main resonance, the 37 KHz mode was selected as example.

All system modes the resonant frequencies becomes less when the nonlinear regimen is reached. This behavior affects both amplitude and phase. In time reversal, phase changes are very important. On the other hand, in monochromatic or burst tone techniques usually only amplitude changes are displayed. For example, in Fig.3 for 37 KHz mode phase is approximately 45º in the low amplitude linear regime. When the amplitude is increased, the phase shifts and becomes near to 0º. For the 36.6 KHz a similar behavior is observed, in linear regime the phase is 150º but in high amplitudes becomes near 45º. This introduce errors into the time reversal process, as shown in (4).

4. Time Reversal Characterization

Classical time reversal process uses a single short ultrasonic pulse to measure the impulse response. After that, the signal is time reversed and retransmitted to the system. Typically the amplitude of the pulse is hundreds of volts, in the previous section is noted that the signals of great amplitude lead to nonlinear regime. Otherwise, when we use low amplitude pulses is difficult to separate the impulse response from background noise. In summary, the use of impulse response can introduce errors in the amplitude and phase determination for the resonant modes. For that reason FDTR technique is used [7], and then the system is identified in frequency domain. The output amplitude in the network analyzer is set to 10 mV in order to guarantee linear behavior in all frequency ranges. After that, the temporal time reversed signal is obtained using the inverse Fourier transform. Experimental setup for measure transfer function is shown in Fig.2 while the final setup to send the temporal reversed signal is shown in Fig.4.

After this calculation, the reversed signal is sent back to the transducer, focusing on the selected point in the front of transducers surface. The signal to be studied is that acquired in the focal point *r*. The absolute of the focused signal can be changed using the output voltage value of the arbitrary waveform generator used to convert the digital signal calculated in the PC in to an analogical output. A typical shape of such a time-reversed signal for three different levels of input voltage is shown in Fig.5. In the lower output level (50 mV in the arbitrary generator gain) the system remains linear. Note the slight peak at the focal point due to the coherent sum of the contributions from different frequency modes.

The amplitude in the diagrams corresponds to the maximum of the arbitrary signal generator (see Fig. 4). To obtain the electric field inside the piezoceramic, 1 V corresponds to 100 KV/m.

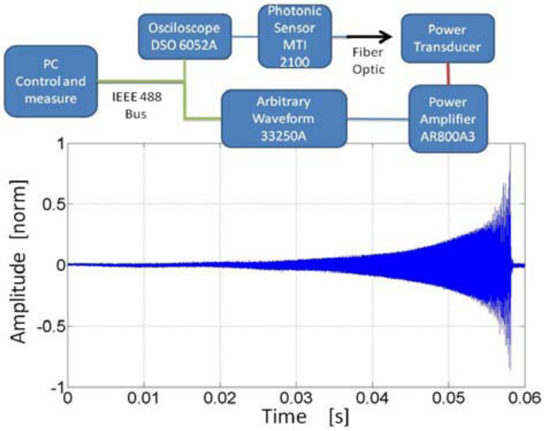

Fig.4 Set up used to send arbitrary temporal signals. Typical reversed signal used in this experience. 32768 points acquired at 500 KHz sample frequency.

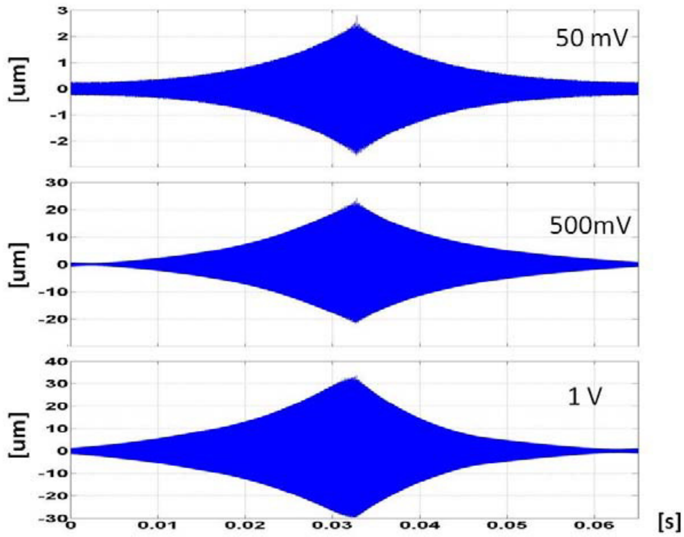

Fig.5 Signal received in focus after time reversal process for different amplitude levels. Note symmetry loss as the applied voltage increased.

A first characteristic of nonlinear behavior associated with the relative phase changes is observed here, as the input amplitude is increased the focused signal loses symmetry respect to center. If the system remains linear, focus amplitude must be proportional to input voltage. The loss of linearity can be associated with a focus amplitude diminution, as was established in (4). Figure 6 shows this evolution, a straight-line drawn from the firsts points acts as an give support to indicate the loss of linearity in the systems response.

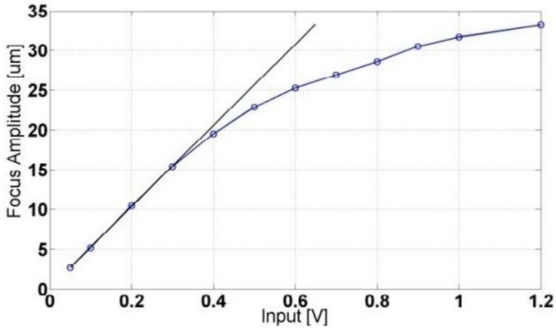

Fig.6 Focus amplitude vs. input voltage. Experimental data are marked by "o", the straight line is placed as a reference. (1 V is equivalent to 100 KV/m inside the piezoceramic).

Finally, another feature that highlights nonlinear behavior is showed. For a linear system the spectrum of the signal recorded in the focus must be the product of the transfer function by its complex conjugate. A zoom of this product is shown in the upper of Fig.7. This represents the theoretical response of the linear system in the time reversal process and is used as a reference to evaluate the effects introduced by the nonlinearities. In the bottom of Fig.7 we show the experimental spectrum acquired when the input voltage is 1 V. In this case, harmonics of the 20 KHz resonance mode are easy to view. But also note the emergence of other frequencies like 7 KHz. This may correspond to a sub-harmonic frequency, typical in nonlinear behavior.

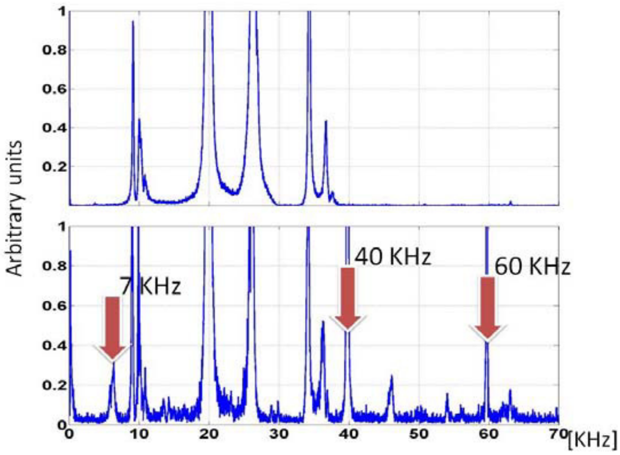

Fig.7 In the top, theoretical expected spectrum. In the bottom experimental spectrum acquired from 1 V input voltage. Note the emergence of new frequencies, especially harmonics of highest amplitude mode (20 KHz).

5. Conclusion

In this work the nonlinear behavior of a Langevin-type power ultrasound transducer working in pulsed regime is analyzed. Time reversal technique was used to obtain the signal to be applied to the transducer. Time reversal is well placed to study nonlinear effects because high strains are obtained in short times. Also time reversal avoids the overheat problem, which is common in high power transducers, and it gives information about the transducer behavior when a pulsed signal is applied.

Three types of effects were discussed. First, the symmetry of the signal recorded at focal spot is lost. Second, the signal amplitude at the focus decreases when the input signal increases. Finally, harmonic frequencies appear in the focus spectrum. The last two effects allow a quantitative evaluation. For the focused signal amplitude, the divergence from the straight line can be used as a nonlinearity measurement. Considering the harmonic frequencies, the relationship between the energy content in the harmonics and the energy in the thickness mode can be used as a harmonic distortion measurement.

The FDTR was used to implement the time reversal. In a linear system, FDTR is equivalent to traditional time reversal based on the impulse response. Whereas, the characterization of the system in FDTR is made in sinusoidal regime using low amplitudes, ensuring a linear behavior in the first half of the time reversal process. In this way, the nonlinear effects are introduced in the second part of the process, when the signal is reemitted.

This work is a first step for the study and the characterization of power ultrasound transducers in the case of wideband pulsed signals.

Acknowledgements

The authors acknowledge FAPESP for financial support.

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